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StarWars Laser Technology Applied to Drilling and Completing Gas Wells

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Abstract

This paper describes results of the first phase of a Gas Research Institute (GRI) funded research program. The overall purpose of this research is to advance a fundamental change in the method currently used to drill and complete natural gas wells applying the U.S. Defense Department's StarWars laser technology. Results of tests conducted at the U.S. Air Force and the U.S. Army's high power laser research facilities are presented.

Initial testing on reservoir rocks conducted with the **M**id **I**nfrared **A**dvanced **C**hemical **L**aser (MIRACL) at the U.S. Army's High Energy Laser Systems Test Facility at White Sands, New Mexico, showed the potential for laser drilling. The laser beam drilled at a speed that indicates penetration could be increased by more than 100 times current rates.

Planned testing for the next phase of this research is to use the **C**hemical **O**xygen-**I**odine **L**aser (COIL) high powered laser invented in 1977 by the U.S. Air Force Research Laboratory in Albuquerque, New Mexico, for air-to-air defense. COIL has gained notoriety as an airborne laser tactical weapon capable of tracking and destroying missiles.

An annotated bibliography was developed for the GRI that comprehensively reviews published laser-rock interaction, current drilling research, and technical data related to laser applications in non-reservoir rocks.[1] Developing commercial applications of StarWars laser technologies has commenced not only in the U.S., but also in Russia and the former Soviet Union.

Introduction

Advances in laser-rock-fluid interactions appear to have been largely ignored in petroleum literature. A search of the SPE Image Library, which contains more than 28,000 papers, listed only two laser references, both of which were more than 25 years old.[2,3] Basic research on high power laser-rock-fluid interactions is being undertaken in order to determine which laser(s) have the required power, portability, reliability, durability, safety and environmental impacts for economically drilling and completing natural gas wells.

Tremendous advances have occurred in laser power generation, efficiency and transmission capabilities that are now being made available for use by the petroleum industry through a U.S. Congressional mandate.[4] The possibility exists to revolutionize drilling for natural gas resources by:

1. Significantly increasing the rate of penetration (ROP)
2. Reducing or eliminating rig day rate, casing requirements, bit life and trip time
3. Providing enhanced well control, perforating and side-tracking capabilities
4. Achieving these breakthroughs with environmentally attractive, safe and cost effective technology.

Laser is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Albert Einstein[5] predicted stimulated emission (generation of photons or discrete bundles of energy via transition between atomic or molecular energy levels) in 1917 but it wasn't until the early 1960's that the first laser was invented. Lasers are basically devices that convert energy of one form to photons (electromagnetic radiation). For example, chemical lasers convert chemical energy to light energy which can be focused into intense laser beams that can in turn be used to spall (fragment), fuse (melt) or vaporize rock depending on input power.

The dissenting and contradictory views towards laser drilling advocated by some people in the petroleum industry are based on limited laboratory studies and experiments that were conducted over 25 years ago when lasers were in their infancy. These early studies were directed at enhancing tunneling machines used in the mining industry. The lasers used in these studies had very low power (less than a kilowatt), created relatively large wavelengths (therefore were difficult to focus), were incapable of transmitting power to the rock face at distances from the laser source, were non-portable and largely unsafe for industrial applications. It is not surprising, using the information gained from tests obtained with these *primitive* lasers, that as recent as 1990, a study conducted on behalf of the GRI suggested eliminating laser drilling from further consideration.[6]

Unfortunately, advances in laser technology do not appear in subsequent petroleum literature and many petroleum engineers have only seen or heard about the early work concerning laser drilling and have therefore not pursued its development.

Motivation for this Research

Rock destruction and removal represents a significant portion of the process for gas and oil extraction. In 1996 alone, over 20,000 wells were drilled in the U.S. (**Figure 1**). Fifty percent of these wells (10,000 wells) were drilled to an average depth of 5,000 feet. This is equivalent to 50 million feet per year or approximately 9000 miles which is larger than the diameter of the earth.[7]

Figure 2 shows the average drilling cost per well by depth interval from 1959 to 1996.[7] A shallow well drilled to a depth of 5000 ft in 1996 cost on average $125,000. So, for the 10,000 shallow wells drilled in 1996, this amounted to a $1.25 billion dollar expenditure. **Figure 3** shows the average cost per foot and average depth per well over this same time period for wells drilled offshore.[7] The average depth has not changed in the last 40 years but drilling costs have increased by an order of magnitude. Rising platform costs, inflation, additional costs for equipment and transportation, and tougher drilling environments have contributed to this rise in drilling costs.

In 1995, Cohen[8] *et al.* quoted a GRI study of 3000 wells drilled in all parts of the world, both on land and offshore, that for deep gas wells (greater than 15,000 ft):

1. 50% of time a gas well drilling rig is on-site is spent drilling the well deeper
2. 20% of time is spent tripping the drill string in and out of the hole to replace bottomhole assemblies
3. 30% of time is spent casing/cementing, conditioning mud, and other operations which do not contribute to being "on bottom, turning to the right."

Gregoli[9] *et al.* (1997) reported results in a GRI Successful Drilling Practices Study (SDP) for seven drilling environments (**Table 1**). Average well costs ranged from $336,000 in the Green River East to $11,000,000 for deepwater exploration in the Gulf of Mexico. Equivalent costs in $/ft for these two regions were $34.50 and $721.00, respectively. ROP's from the study ranged from 10.42 to 34.75 ft/hr.

It is clear from the above studies that major reductions in drilling costs can be obtained by drilling faster and by reducing requirements to remove the drill string. Moreover, by drilling horizontal laterals in existing wells could gain access to unrecovered reserves.

U.S. Congressional Mandate– Access to StarWars Technology

Advances in laser technology have flourished since 25 years ago, largely through the expanded knowledge of atomic physics, invention of fiber optics and, more recently, the efforts of the U.S. Department of Defense's StarWars projects. The results of these efforts were the development of high power (megawatt scale), low wavelength tactical lasers for satellite warfare including tracking and destroying offensive ballistic missiles (such as the Scud used by Iraq during Operation Desert Storm).

Since the end of the Cold War, the U.S. Congress has mandated that these technologies be made available to industry.[4] For this reason, the U.S. Air Force Research Laboratory headquartered at Kirtland Air Force Base, New Mexico and the U.S. Army **H**igh **E**nergy **L**aser **S**ystems **T**est **F**acility (HELSTF) at White Sands Missile Range, New Mexico are making available these technologies to enhance the American industrial and technological competitiveness. CRADAs (**C**ooperative **R**esearch **a**nd **D**evelopment **A**greements) have been established at a funding level equal to that provided by the GRI for this research.

Features of Modern High Power Lasers

A laser is a source of electromagnetic coherent radiation, transforming different kinds of energy (electrical, chemical, heat, etc.) into the energy of light. Coherency means phase correlation in time (temporal coherency) and space (spatial coherency) of the propagation process for the electromagnetic waves.

One of the consequences of temporal coherency is a very narrow spectral line for laser radiation, called monochromatic radiation. The wavelength λ of laser radiation depends on the laser's active medium, ranging from 0.1 μm to 10^3 μm and spans the ultraviolet, visible, infrared and submillimeter ranges of the spectrum.

Lasers can operate in continuous-wave (CW), pulsed and repetitively pulsed, (RP) modes. The main energetic parameter for a CW laser is the output power P, for a pulsed laser the output energy Q, and for a laser operating in RP mode the average power P and pulsed energy Q.

Laser pulse length (duration) τ for pulsed lasers can vary from 10^{-2} seconds down to a few femtoseconds (10^{-15} seconds). Laser pulse energy is also characterized by peak power P_{peak} defined as pulse energy to pulse length ratio:

$$P_{peak} = Q/\tau \quad (1)$$

For RP mode, the average power is determined by laser pulse energy and pulse repetition rate:

$$f = 1/T \quad (2)$$

where f is the frequency and T is the time interval between the beginning of the laser pulses:

$$P_{avg} = Q/T = P_{peak} \cdot \tau/T \quad (3)$$

Laser beams are also characterized by angular divergence Θ [radian], which can be roughly defined as a ratio of the unfocused laser radiation spot diameter (at far distance) to the distance from the laser. The best laser beam divergence is limited by the diffraction limit:

$$\Theta_{dif} = \lambda/D \quad (4)$$

where D is the laser diameter at the exit of the laser (or optical system connected with the laser). A Θ = 0.1 - 0.01 mrad is considered to be representative for high power lasers. Low beam divergence is of practical concern for gas well drilling and completions because first, the laser system can be placed far away from the zone of rock destruction, and, second, the laser beam can be focused in a very small spot with a diffraction limited diameter.

Laser radiation can be focused by an optical system, including lenses and spherical or parabolic mirrors, onto the rock surface in a spot with a size of:

$$\ell = \Theta \cdot F \quad (5)$$

where F is focus length for the optical system applied. The minimum size of ℓ is limited by $\ell_{min} = \lambda$.

Laser radiation focused onto the rock surface is characterized by energy density:

$$q = Q/S \quad (6)$$

where $S \approx \ell^2$, or by intensity (power density):

$$I = P/S \quad (7)$$

Due to the monochromatic property of laser light and the ability to focus it into a small spot size gives the unique advantages of using lasers to spall, fuse or vaporize rock depending on the energy or power density.

Laser Energy Transfer

There are three processes by which laser energy is transferred into rocks:

1. Reflection
2. Scattering
3. Absorption

It is the absorbed energy that gives rise to rock heating and destruction. Reflection and scattering represent the losses of energy in the process of laser rock destruction. The degree to which energy is lost to reflection and scattering dictates the effectiveness of the laser's ability to spall, fuse or vaporize rock. In addition to the energy losses from reflection and scattering, two other phenomena impact transfer of laser energy into the rock:

1. Blackbody radiation - When a rock temperature grows high, the rock itself turns into an intense source of radiation. At high rock temperatures over an extended area of heating, a substantial fraction of the incident energy can be emitted back by the surface of the rock as blackbody radiation.

2. Plasma screening – High power laser radiation can also cause the formation of a laser plasma (ionized gas) over the surface irradiated. The laser plasma reflects, scatters and absorbs the incident laser radiation and prevents energy from getting to the rock face.

The feasibility of laser rock destruction derives from the following properties of rocks which have been experimentally verified:

1. Low reflectivity of rocks resulting in good coupling of laser radiation with rocks
2. Deep penetration of laser energy into rock resulting in volumetric absorption of laser energy
3. Low thermal conductivity of rocks resulting in effective heating.

Laser Candidates for Drilling and Completion

There are only a few types of high power lasers developed at the moment that appear attractive for natural gas drilling and completions:

1. **HF(DF)** laser: The hydrogen fluoride (HF) and deuterium fluoride (DF) lasers operate at wavelengths between λ = 2.6 – 4.2 μm. The U.S. Army's MIRACL laser which was used for the first series of tests on reservoir rocks (see Experimental Results section of paper) was the first megawatt-class, CW chemical laser developed in the free world.[10]

2. **COIL** laser: The U.S. Air Force Research Lab's **C**hemical **O**xygen **I**odine **L**aser operates at a wavelength of $\lambda = 1.315$ µm. Initially developed in 1977, this high power laser which operates in CW mode, has evolved and matured to a sophisticated state for military and now for industrial applications. It has gained notoriety for its **A**irborne **L**aser (ABL) tactical capabilities where it will be placed onboard a Boeing 747 aircraft and used to track and destroy missiles with megawatt power. It has successfully tracked at a range of 31 miles (50 kilometers).[11] Obviously, this type of precision and range could eliminate many of the well control, side-tracking and directional (lateral) drilling problems which are often encountered in drilling or recompleting natural gas wells.

3. **CO_2** laser: The carbon dioxide laser operates at a wavelength $\lambda = 10.6$ µm. It can operate either in CW or RP modes. Its average power is up to 1 MW. When operating in RP modes, its pulse length can vary between 1-30 µs.[12] The significant advantage of the CO_2 laser is its durability and reliability. One of its problems is that because of its large wavelength, it is greatly attenuated through fiber optics.

4. **CO** laser: The carbon monoxide laser operates at a wavelength $\lambda \cong$ 5-6 µm. It can also operate in both CW or RP modes. Its average power achievable is up to 200 kW and pulse length can vary between 1-1000 µs.[13] The first overtone CO laser operates in CW or RP modes at a wavelength $\lambda =$ 2.5-4.0 µm. The ability to achieve lower wavelengths is important because the effect of surface screening by the laser plasma is reduced, as the wavelength of the laser radiation becomes shorter.

5. **FEL** laser: The **F**ree **E**lectron **L**aser operates on high energy electrons that lack discrete energy levels and therefore allows tuning to virtually any wavelength in CW mode. Some scientists consider it to be the high power laser of the future.[14] The ability to adjust the wavelength of the laser radiation would allow optimization for such effects as reflection, scattering, absorption, blackbody radiation and plasma screening.

6. **Nd:YAG** laser: The neodymium: yttrium aluminum garnet laser operates at a wavelength $\lambda = 1.06$ µm. Currently only 4 kW industrial lasers are commercially available. Trends in the R&D of this laser indicates the feasibility of launching the laser with output powers of 10 kW and higher.[15]

7. **KrF** (excimer) laser: The krypton fluoride *excimer* laser operates at a wavelength $\lambda = 0.248$ µm. The term excimer is used to describe this laser because the component atoms krypton and fluoride in this diatomic molecule are bound in the excited state, but not in the ground state. That property makes this laser operate in the RP mode. The maximum average power is 10 kW with a pulse length of 0.1 µs.[16]

The choice of the laser(s) for applications to industrial rock destruction is limited. Only these seven types of lasers are being considered as a candidate (or candidates) for gas well rock drilling and cutting.

Targeted Literature Review

A review of published material on laser-rock interaction and destruction, which were carried out since the beginning of the 1970's, was done and published as part of this phase of the GRI project.[1] Most of the research was accomplished during the timeframe from early 1970 through the mid-1980's.

The main conclusion from the review is that the application of high power lasers, especially infrared lasers, for rock destruction is attractive because of the excellent conditions for laser energy transfer into rocks. These conditions include good absorptivity by rocks; relatively deep penetration of radiation into rocks and low rock heat conductivity.

High power lasers can be used in various ways for destroying rock: rock weakening with further application of mechanical tools and by direct rock destruction via ablation. Several methods of ablating rock are available and each may have specific application for natural gas drilling and completion (spalling, fusing or vaporizing).

Experimental Results

In order to determine whether high power lasers could be used to drill both conventional wellbore size holes (six inch diameter) and smaller perforation size holes (two inch diameter), two 9 Darcy dry sandstone samples were prepared. The rectangular samples measured twelve inches square by three inches deep.

In the first experiment, a six inch diameter CW beam was generated by the U.S. Army's MIRACL having a wavelength of 3.8 µm and output power that ramped up from 600 to 1200 kW (average power of 900 kW) and aimed head-on against the three inch thick sandstone slab. The objective was to observe the amount of rock removed by using a full beam at conventional wellbore diameter size. Published data (circa 1970) used to calculate depth of penetration suggested that a laser beam at this power density would not penetrate the rock. After a 4.5 second burst of the beam, a hole was blasted 2.5 inches through the sandstone sample, removing 5.5 pounds of material at an equivalent ROP of 166 ft/hr. **Figure 4** shows three photographs of the sample following the test.

In the second experiment, the objective was to simulate horizontal drilling or perforating using the beam and view its penetration into the rock. The other three inch dry sandstone slab was used, but this time a concave mirror was used to redirect the MIRACL beam, focus it down to a two inch diameter spot size and send it to the side of the sandstone slab. The MIRACL beam output power was 500 kW. Following two, 2-second laser blasts, a six inch penetration was achieved with an equivalent ROP of 450 ft/hr. **Figure 5** shows three photographs of the sample following the test. Permeability measurements made before and after the test saw no reduction to permeability in or around the hole. This promising result suggests there could be virtually no damage to the rock formation using this horizontal technique, which would allow for a good flow rate of natural gas into the wellbore.

Results of these two tests demonstrated that high power lasers were very effective for drilling and invalidated the published data used to calculate penetration depths.

Research Focus

Because of the success achieved with the initial testing, the next phase of the research will be to evaluate:

ROCK-FLUID SYSTEMS

1. Delivery system – how to get laser to location and downhole
2. Laser behavior in fluids – oil, water, hydrocarbon gas, mud
3. Rock type – sandstone, shale, limestone, salt
4. Rock properties – porosity, permeability, mineralogy
5. Stress

LASER SYSTEMS

1. Type of laser
2. Wavelength
3. Mode of operation – CW or RP
4. Power density
5. Beam profile

Conclusions

It is important to recall what transpired when cable tool drilling was contemplated being replaced by the rotary drilling rig at the turn of the century. There was a great resistance by the industry to adopt rotary drilling. It required people with vision, persistence and financial ability to change the tide in thinking. Now is the time for a similar hurdle to be overcome for laser drilling.

Basic research on high power laser-rock-fluid interactions are being undertaken to determine which laser(s) have the required power, portability, reliability, durability, safety and environmental impacts for economically drilling and completing natural gas wells.

The following sections summarize some of the main observations and conclusions that were derived from this initial phase of research:

1. ***Features of Modern High Power Lasers*** - The choice of lasers for application in natural gas well drilling and completion is limited to seven types of lasers.

2. ***Laser Energy Transfer into Rocks*** – Infrared radiation is more attractive for laser rock destruction than visible radiation not only because of the availability of high power lasers in the infrared, but also as a consequence of the properties of rocks.

3. ***Physical and Chemical Processes Characteristics in Rocks that have been Heated by Laser Radiation*** - The physics and chemistry of laser rock interaction is very complicated. Systematic experiments on laser rock interaction with various lasers, operating in various modes, with various rocks should be done for better understanding of the physical and chemical phenomena associated with rocks under the influence of laser radiation.

4. ***Rock Destruction under the Influence of Laser and Non-coherent Radiation*** - The experimental results can be used for a rough estimate of the energy consumption and drilling rate that may be possible using lasers.

The information that was reviewed concerning laser-rock interaction was based on results obtained with relatively low power lasers. The impacts of high power laser-rock-fluid interactions have not been studied. This basic research will provide the foundation on which to determine the benefits of using StarWars laser technology for drilling and completing natural gas wells.

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Nomenclature

D = diameter, L
F = focal length, L
f = frequency, 1/t
I = power density, m/t^3
ℓ = spot size, L
P = power, mL^2/t^3
Q = energy, mL^2/t^2
q = energy density, m/t^2
S = surface area, L^2
T = time interval between pulses, t
λ = wavelength, L
Θ = angular divergence, radian
τ = pulse length, t

Laser Modes of Operation:
CW = continuous wave
RP = repetitively pulsed

Subscripts

avg = average
dif = diffraction
min = minimum
peak = peak

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SI Metric Conversion Factors

inch	X 2.54*	E+00 = cm
ft	X 3.048*	E–01 = m
mile	X 1.609 344*	E+00 = km
lbm	X 4.535 924	E–01 = kg
Btu (mean)	X 1.055 87	E+03 = J
md	X 9.869 233	E–16 = m^2
horsepower	X 7.456 999	E–01 = kW

*Conversion factor is exact.

TABLE 1 - GRI SUCCESSFUL DRILLING PRACTICES

Study Area	Days(1)	Average Measured Depth (ft)	Well Cost(2) ($000)	ROP (ft/hr)(3)	Cost ($/ft)(4)
Green River West (Wyoming)	18	12,263	430	28.83	35.00
Green River East (Wyoming)	12	9,731	336	34.75	34.50
Arkoma (Oklahoma)	61	14,900	1,888	10.42	126.70
Anadarko (Oklahoma)	36	11,150	580	13.25	52.00
Deepwater Exploration (Gulf of Mexico)	50	15,250	11,000	12.71	721.00
Wilcox Lobo Trend (Texas)	12	9,244	403	31.33	43.60
Extended Reach Drilling (Gulf of Mexico)	28	19,300	2,595	28.75	134.00

(1) Spud Date to Total Depth Date
(2) Cumulative cost to setting of production casing, includes casing cost
(3) Average Measured Depth divided by Days (1) divided by 24
(4) Well Cost (2) Divided by Average Measured Depth

Source: Modified version of Table 2 of Ref. 9

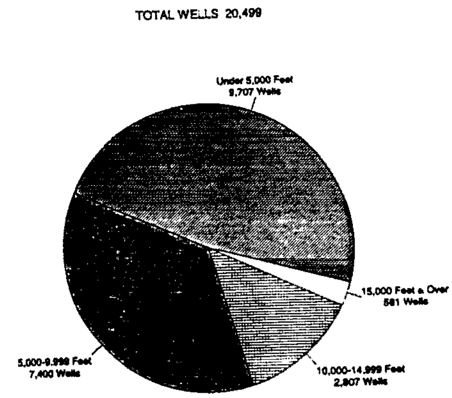

Fig. 1 – Depth Intervals of Wells Drilled in the United States in 1996. (Ref. 7)

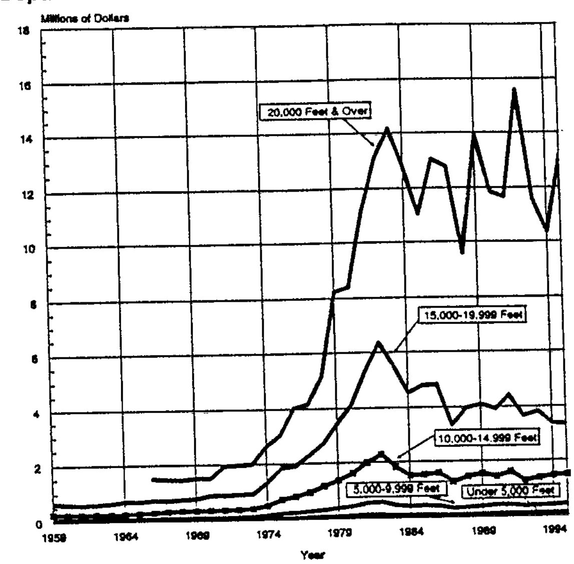

Fig. 2 – Average Cost Per Well by Depth Interval in the United States from 1959 to 1996 (Ref. 7)

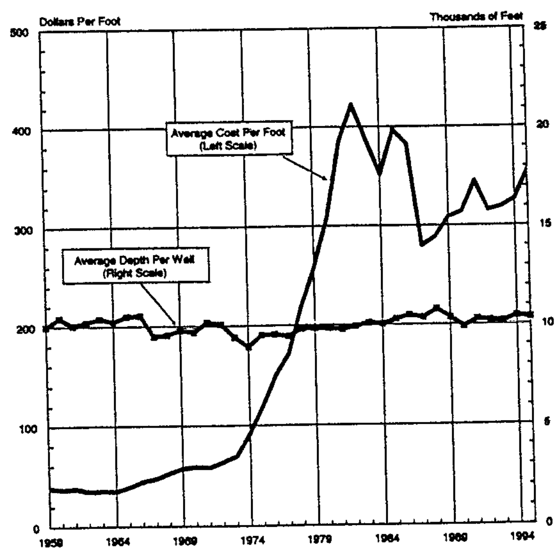

Fig. 3 – Estimated Cost of Drilling and Equipping Offshore Wells in the United States from 1959 to 1996 (Ref. 7)

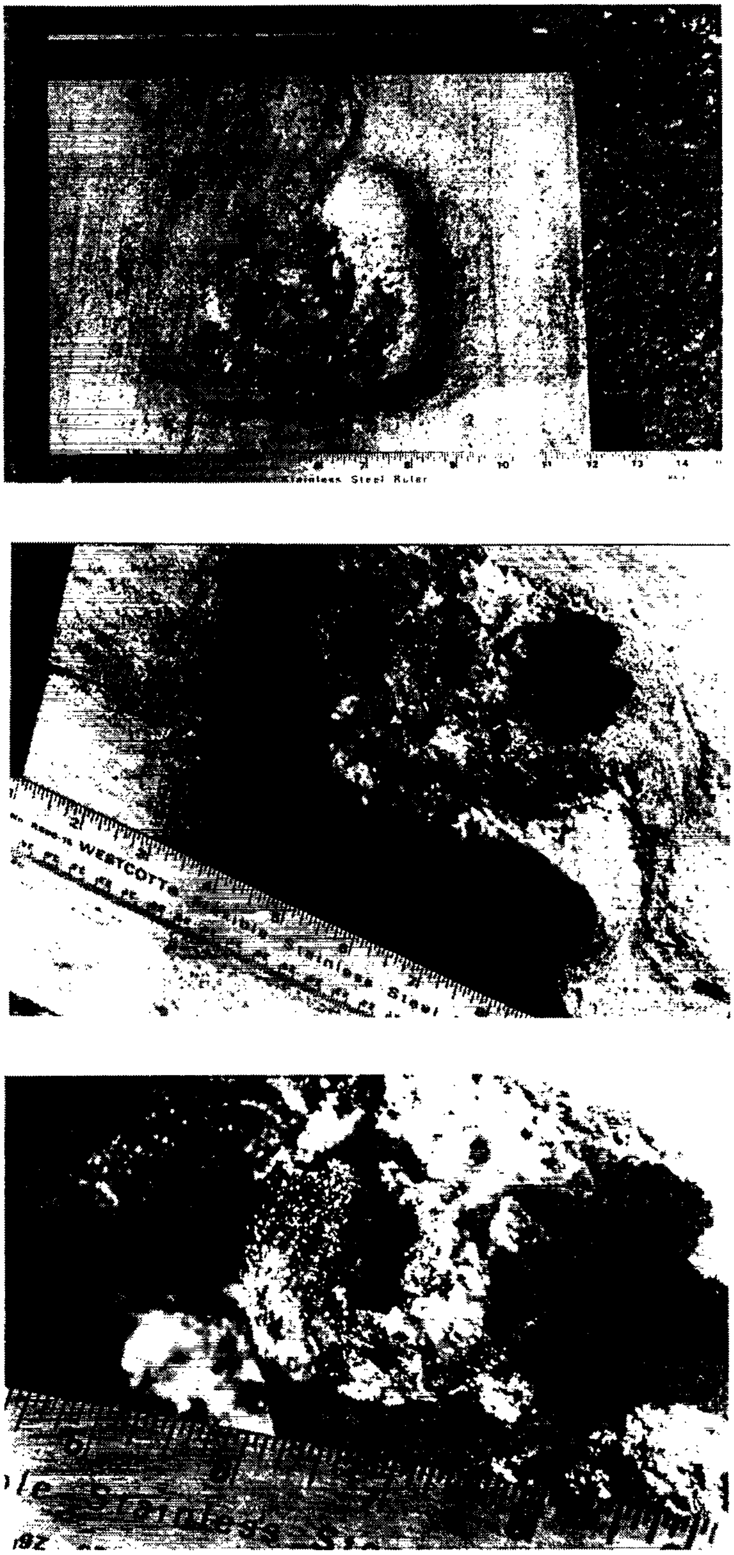

Fig. 4 – Photographs of 9 Darcy Dry Sandstone Subjected to MIRACL Laser, Six Inch Diameter, January 21, 1998

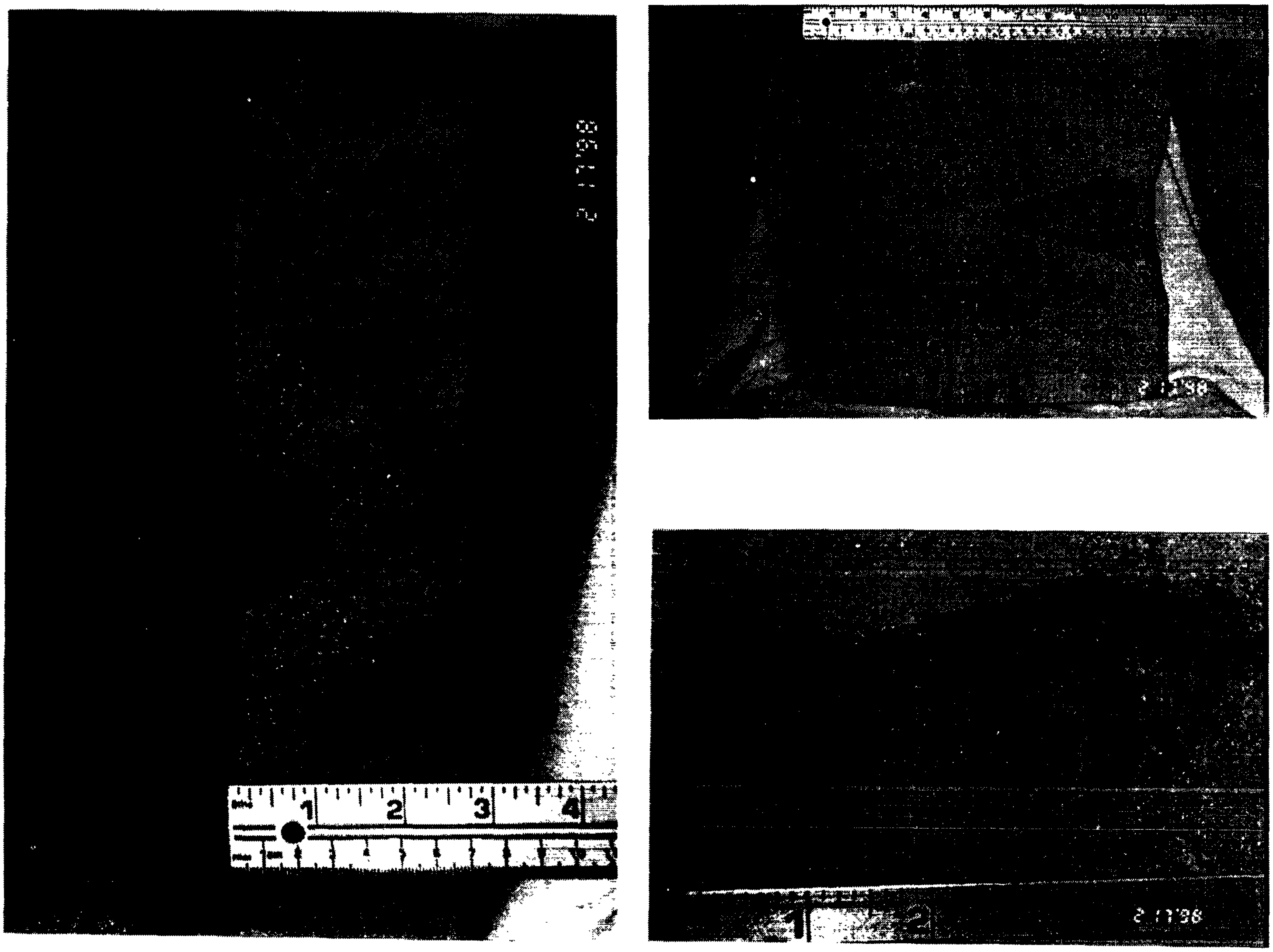

Fig. 5 – Photographs of 9 Darcy Dry Sandstone Subjected to MIRACL Laser, Two Inch Diameter, January 21, 1998